(4)

DNA-TR-86-70

DEVELOPMENT OF A DAMPED BAR GAUGE FOR LONG-DURATION STRESS-PULSE RECORDING

R. S. Wilson
S-CUBED
A Division of Maxwell Laboratories, Inc.
P.O. Box 1620
La Jolla, CA 92038-1620

25 February 1986

Technical Report

CONTRACT No. DNA 001-82-C-0159

Approved for public release;
distribution is unlimited.

THIS WORK WAS SPONSORED BY THE DEFENSE NUCLEAR AGENCY
UNDER RDT&E RMSS CODE B345083466 J11AMXJI00023 H2590D.

Prepared for
Director
DEFENSE NUCLEAR AGENCY
Washington, DC 20305-1000

Destroy this report when it is no longer needed. Do not return to sender.

PLEASE NOTIFY THE DEFENSE NUCLEAR AGENCY, ATTN: STTI, WASHINGTON, DC 20305-1000, IF YOUR ADDRESS IS INCORRECT, IF YOU WISH IT DELETED FROM THE DISTRIBUTION LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION.

CUT HERE AND RETURN

DISTRIBUTION LIST UPDATE

This mailer is provided to enable DNA to maintain current distribution lists for reports. We would appreciate your providing the requested information.

- ☐ Add the individual listed to your distribution list.
- ☐ Delete the cited organization/individual.
- ☐ Change of address.

NAME: ____________________

ORGANIZATION: ____________________

OLD ADDRESS	CURRENT ADDRESS
____________________	____________________
____________________	____________________
____________________	____________________

TELEPHONE NUMBER: ( ) ____________________

SUBJECT AREA(s) OF INTEREST:

____________________	____________________
____________________	____________________
____________________	____________________

DNA OR OTHER GOVERNMENT CONTRACT NUMBER: ____________________

CERTIFICATION OF NEED-TO-KNOW BY GOVERNMENT SPONSOR (if other than DNA):

SPONSORING ORGANIZATION: ____________________

CONTRACTING OFFICER OR REPRESENTATIVE: ____________________

SIGNATURE: ____________________

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY: N/A Since Unclassified	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A Since Unclassified	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): SSS-R-85-7097	5. MONITORING ORGANIZATION REPORT NUMBER(S): DNA-TR-86-70
6a. NAME OF PERFORMING ORGANIZATION: S-CUBED, A Division of Maxwell Laboratories, Inc. — 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Director Defense Nuclear Agency
6c. ADDRESS (City, State, and ZIP Code): Post Office Box 1620 La Jolla, CA 92038-1620	7b. ADDRESS (City, State, and ZIP Code): Washington, DC 20305-1000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION — 8b. OFFICE SYMBOL (If applicable): SPWE/Frankel	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: DNA 001-82-C-0159
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO 62715H; PROJECT NO J11AMXJ; TASK NO I; WORK UNIT ACCESSION NO DH006447

11. TITLE (Include Security Classification)
DEVELOPMENT OF A DAMPED BAR GAUGE FOR LONG-DURATION STRESS-PULSE RECORDING

12. PERSONAL AUTHOR(S)
Wilson, R.S.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 820401 TO 840801	860225	30

16. SUPPLEMENTARY NOTATION
This work was sponsored by the Defense Nuclear Agency under RDT&E RMSS Code B345083466 J11AMXJI00023 H2590D.

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
20	11	
14	2	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Bar Guage,
Damped Bar Guage,
Long-Duration Stress Measurements.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Various methods for reducing the amplitude of the stress-pulse reflection from the end of a Hopkinson bar gauge have been evaluated with the intent of extending the useful recording time of the gauge without physically lengthening the dump bar. This work is the extension of a previously described acoustic technique into the multi-kilobar stress range. Preliminary success was obtained in laboratory testing of a 91 cm long attenuator of soft, steel-filled epoxy, precisely shaped to maintain a constant acoustic impedance along the bar.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: Sandra E. Young	22b. TELEPHONE (Include Area Code): (202) 325-7042 — 22c. OFFICE SYMBOL: DNA/CSTI

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1
INTRODUCTION

There is considerable interest in making long-duration pressure measurements on large-scale, high-explosive (HE) tests and underground nuclear tests. At present, the best gauge for short durations is the Hopkinson bar gauge. The recording time for such a gauge is limited to the time required for a sound wave to make one round trip in the dump bar. At that time, the reflection of the incident pulse from the far end of the gauge will degrade the record. For gauges of reasonable lengths this limits the recording time for low-noise records to approximately 1 ms. Edwards et al. [2] have shown that by tapering the dump bar and coating it with an absorbing medium of an appropriate shape, the reflection from the end of the bar can be reduced to an insignificant level. However, Edwards worked only at very low pressures. The purpose of this project was to extend Edwards' technique to the higher stress levels appropriate to HE and nuclear testing. The goal was a gauge which would accommodate pressure pulses up to 10 kbar, and record for 10 ms.

This work was divided into three tasks as follows:

1. Review previous efforts to produce an attenuated reflection in the dump rod of a Hopkinson bar gauge.

2. Design and produce a damped bar gauge for high-stress environment measurements. Design considerations should include an evaluation of the effects of the strength of the damping material, and of its bond to the dump bar, as well as basic analytical calculations of bar gauge response.

3. Test the effectiveness of absorption and adherence of bar gauge dump rod coatings by carrying out appropriate field tests.

SECTION 2
BACKGROUND

The Hopkinson bar gauge uses the elastic propagation of a pressure wave along a thin rod to deliver the signal from a pressure environment to a sensor, typically a piezoelectric crystal. This rod is known as the input bar. The sensor is backed by another bar, the dump bar, into which the pressure wave passes. This causes the sensor to experience the same stress as was developed in the bar. When the pressure pulse reaches the end of the dump bar, it will reflect and create a tension wave which propagates back toward the sensor, where it will interfere with any incident wave present at that time and degrade the measurement. Thus, the length of the dump bar and the wave speed within the bar determine the maximum interference-free recording time of the gauge. To obtain a 10 ms recording time from a conventional Hopkinson gauge, the dump bar would have to be 25 m long, hardly a practical length for routine field use.

For the relatively low pressures at which he worked, Edwards found that a pressure pulse could be transferred from the elastic dump bar to an absorbing medium surrounding it, without a reflected wave developing, if the two materials had very specific shapes. Once this has been done, an arbitrarily long recording time can, in principle, be provided simply by making the absorbing medium long enough to attenuate the pulse to an insignificant level before it reflects from the end and couples back into the dump bar.

According to elementary acoustic theory, no reflection of a sound wave will occur at the interface of two different bars providing the product of acoustic impedance and cross-sectional area is the same on each side of the interface. For a conically tapered dump bar, this condition leads to the following equation for the radius of the absorbing medium, or attenuator, as a function of position along the bar:

$$\frac{x^2}{L^2 Z_b/(Z_b - Z_a)} + \frac{r^2}{Z_b r_0^2/Z_a} = 1$$

where,

- x = Position along the bar, measured from the pointed end
- r = Radius of the attenuator
- r_0 = Maximum radius of the tapered bar
- L = Length of the taper
- Z_a = Impedance of the attenuator
- Z_b = Impedance of the bar

This is the equation of an ellipse whose shape is determined by the impedance of both the rod and the attenuator; thus, it is necessary to measure the sound speed and density of each of these materials to determine the correct shape for the attenuator.

This was Edwards' so-called "long-duration gauge." He used a conically tapered lead bar with an ellipsoidal attenuator of Picien wax and presented in his paper a waveform which showed no indication of a reflection from the dump bar assembly for a time interval an order of magnitude longer than the ring-free time of a bare lead dump bar. A conceptual diagram of the damped Hopkinson bar gauge is shown in Figure 1. Split bars with quartz sensors were used in all of the tests because they have a high sensitivity and low hysteresis. Ytterbium grids on split bars or strain gauges on non-split bars can and would be used at higher stress levels.

It should be pointed out that the derivation of attenuator shape ignores the details of the bar-attenuator interface where there is a local impedance mismatch, and assumes plane wave propagation along the axis of the bar and attenuator assembly. In general, the propagation will not be planar, since the two materials may have significantly different sound speeds. A rough estimate of the limit this places on the rise time of the pressure signal can be made by assuming that planar propagation occurs for wavelengths greater than 10 bar diameters. This produces a frequency limit of approximately 80 kHz in a 6 mm diameter steel bar, but only 3 kHz in a 3 cm diameter plastic attenuator whose sound speed is 1 mm/μs. The latter corresponds to a rise time greater than 100 μs, which is an order-of-magnitude longer than the rise time of which a bar gauge is capable.

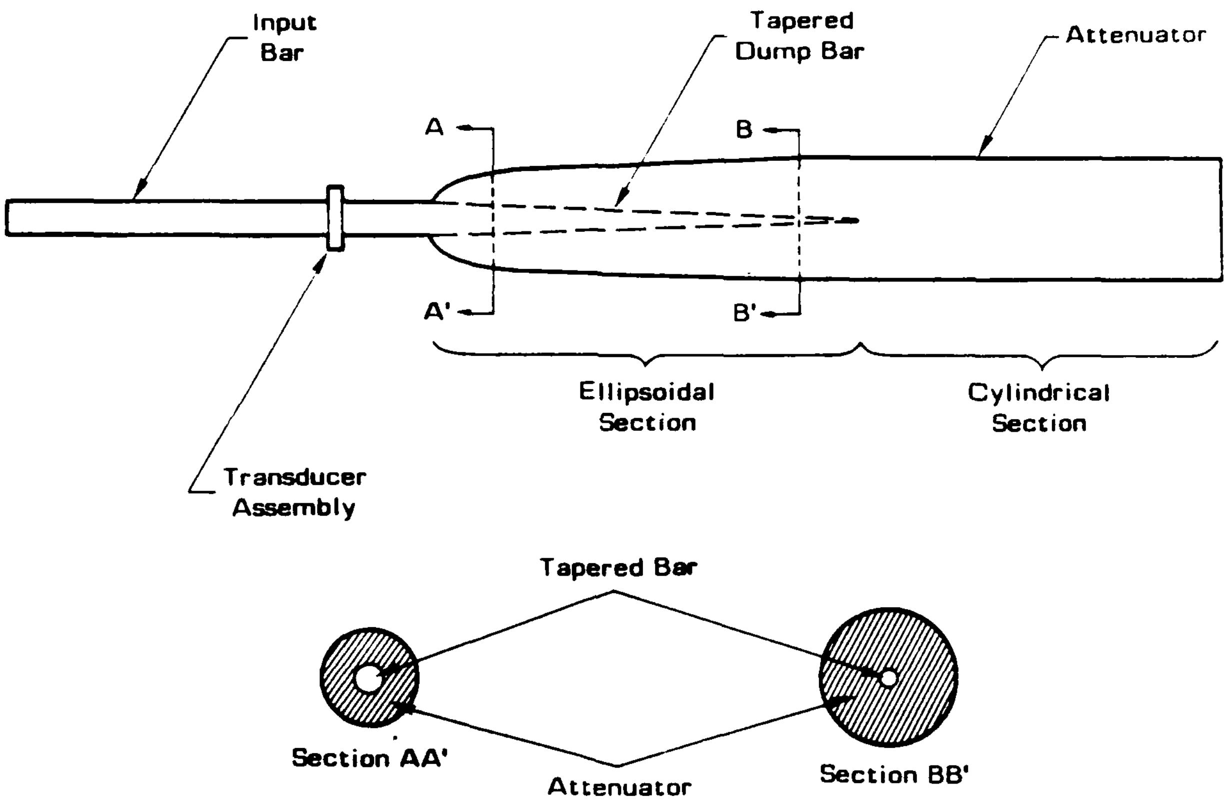


Figure 1. Damped bar gauge. The ellipsoidal shape of the attenuator allows a pressure pulse to couple into it frcm the tapered bar without generating a reflection. The cylindrical section at the end of the attenuator may be required to adequately absorb the pulse.

The long-wavelength assumption used to derive the ellipsoidal shape is not strictly valid. However, the extent to which deviations from plane-wave propagation affect the gauge response is not known and appears to be best determined experimentally.

There are two distinct aspects to the problem of developing a damped bar gauge for high pressures. First, the pressure wave must be coupled from the dump bar into the absorbing material without reflection, and withcut causing the absorbing material to become unbonded from the dump bar. And, secondly, it must be attenuated in the absorbing material so that it cannot reflect from the end of the assembly and couple back into the tapered bar. These two problems were addressed separately in this project.

SECTION 3
LITERATURE REVIEW

Under Task 1, a review was made of previous efforts to reduce the reflection in the dump bar of a Hopkinson bar gauge. However, very little published information on this specific topic was found and the literature search was expanded to include the theory and technique of acoustic damping in general.

Papers by Harpavat [5] and McIntosh [8] referenced Edwards' work but neither described use at high stress levels. Ragland [12] also references Edwards' work and presents a description of a bar gauge having a cylindrical (not tapered) dump bar of tin potted in silicone rubber, which also had a simple, cylindrical shape. His paper shows what he described as a "remarkable" result: "no significant signals due to reflected waves from the end of the tin appear .... apparently, the elastic waves in the tin are attenuated with the aid of the silicone rubber, and thus no further design features are needed for long duration operation". Presumably, the "design features" he referred to are the special shapes of the dump bar and the attenuator in Edwards' gauge.

Unfortunately, Ragland's work, like Edwards', was restricted to the very low pressure range (on the order of 10 bars) so little additional information is obtained, except that the need for the special shapes is in question.

Several references were found on the analysis of waves along bonded layers and bonded concentric cylinders, including the effects of debonding on the propagation of the waves [1, 4, 6, 11, 14]. A theoretical treatment for handling scattering from spherical inclusions in an otherwise homogenous medium is presented by Metha [9]. His theory agrees well with experimental measurements of the velocity and attenuation of P waves in fluid-solid suspensions. The attenuation of pressure pulses by geometrical dispersion in composites was studied by Peck [10]. He also considered the more complex question of attenuation by various fracture processes which can occur specifically because of the inhomogeneity of composite materials. Several papers by Russian authors [3, 7, 13] were found that consider specific problems in acoustic damping and shock absorption with emphasis on the damping properties of alloys.

With the exception of Ragland's paper [12], little information relating directly to the problem of attenuating the reflection in a Hopkinson bar gauge was found. Most of the literature relating to this topic is concerned with the more common problem of acoustic attenuation, and thereby avoids the necessity of dealing with high-level stresses. It was apparent from the inception of this work that the major effort would be experimental; the lack of published material was, therefore, not a serious impediment.

SECTION 4
EXPERIMENTAL WORK

4.1 VERIFICATION OF EDWARDS' TECHNIQUE AT KILOBAR STRESS LEVELS.

The following broad classes of materials were considered for use as the attenuator:

- Transparent Plastics
- Filled Plastics
- Fiber-Wound Plastic-Bonded Coatings
- Porous Plastics
- Porous Metal

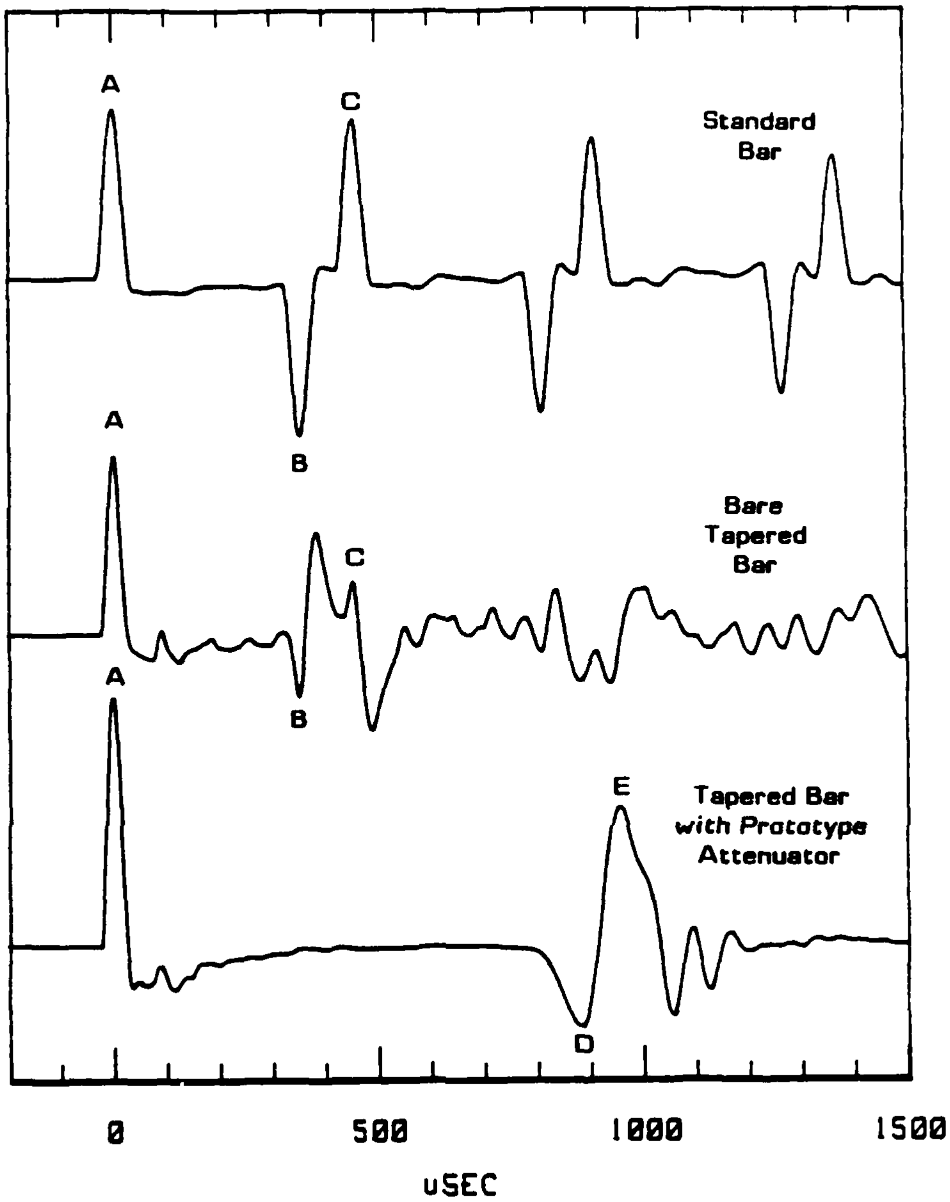
Transparent plastics were considered because they provide a convenient means of studying the problem of fracturing of the bond between the plastic and the tapered bar. A simple, single-component plastic, however, was not expected to be at all optimum as an attenuator. With filled plastics, multi-point scattering from small particles having a density considerably different from the encapsulating material was expected to provide attenuation. In a fiber-wound, plastic-bonded coating, tension in the winding should be able to maintain normal strength and shear coupling by friction, even if the bond to the tapered bar is broken. Porous materials were considered because scattering from the air-filled voids, as well as heating of the air in the voids when compressed, should provide attenuation.

For preliminary tests of the bonding problem, 91 cm long, tapered and cylindrical bars were obtained of Type 6150 steel. This steel, which has a measured sound speed of 5.2 mm/μs, was used to construct three quartz bar gauges. For reference, one gauge was made of the conventional design with a cylindrical dump bar; two gauges were made with the tapered dump bars, one with the bar bare and one with it encapsulated in a plastic attenuator. The attenuator was made of CIBA epoxy, cast about the tapered bar in a cylindrical mold. It was then machined and hand-lapped to the required ellipsoidal shape. CIBA is a very strong, rigid, transparent epoxy extensively used in the production of gauges for shock wave measurements. In all three gauges, the input bars were 25 cm long and the dump bars were 91 cm long. The CIBA attenuator did not extend beyond the end of the tapered bar.

Initial tests of these gauges were made at very low stress levels by dropping a steel ball onto the input bar. The results are shown in Figure 2. The standard gauge produced the very clear multiple reflections shown in the upper trace. In the center trace, the bare tapered dump bar is seen to have caused the reflections to become considerably more complicated, although the arrival time of the first reflection from the end of the bar was unchanged. However, the presence of the epoxy attenuator completely eliminated the reflections from the end of the steel bar at 350 μs, as shown in the bottom trace. At about 900 μs, the large reflection from the end of the CIBA was recorded.

Higher-pressure tests were then made on a drop-bar tester. Figure 3 shows the signals from the standard and damped gauges. The drop-bar used for this test produced a pressure pulse lasting 1.1 ms. As shown on the upper trace, the useful record from the standard gauge ends 350 μs, when the dump bar reflection arrives back at the sensor. But, the damped gauge shows a flat response at that time, and provides a useful signal until the much later reflection from the end of the attenuator reaches the sensor at 900 μs.

The elimination of the reflection from the end of the tapered steel bar in these tests means that the pulse was completely coupled into the plastic. The long delay introduced into the arrival time of the reflection from the end of the attenuator, relative to the bare bar, implies that the coupling into the attenuator occurred promptly after the pulse entered the tapered region, and that the 91 cm long bar was probably unnecessarily long. Further testing of this gauge produced no failure of the attenuator or its bond to the tapered steel bar at pressures up to 2 kbar, and demonstrated that Edwards' technique could be extended to the kilobar stress range. As expected, however, CIBA proved to be a very poor attenuator.



A. Input Pulse
B. Reflection of A from End of Dump Bar
C. Reflection of B from End of Input Bar
D. Reflection of A from End of Plastic Attenuator
E. Reflection of D from End of Input Bar

Figure 2. Drop-ball test results from bar gauges having three different dump bar configurations. The absence of peak B in the lower trace indicates the input pulse was completely coupled into the plastic attenuator.

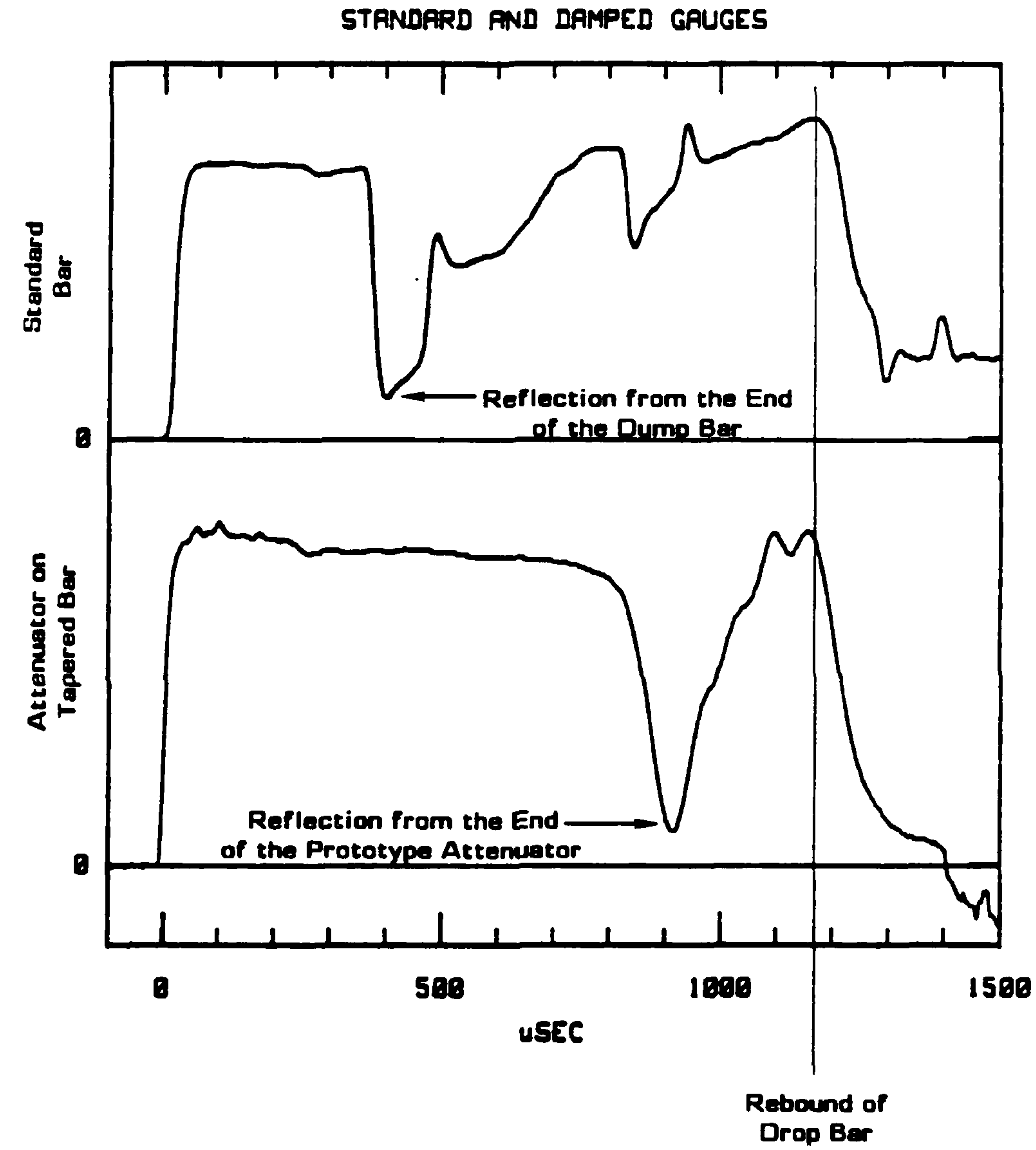


Figure 3. Results of drop-bar tests on the standard and damped gauges. The absence of the reflection at 400 μs in the lower trace indicates the pulse was completely coupled form the tapered dump bar into the plastic attenuator. The peak pressure is approximately 0.8 kb.

4.2 ATTENUATOR DEVELOPMENT.

Two classes of materials were considered as candidates for true attenuators: metal-filled epoxies and porous compounds. Two metal-filled epoxies were evaluated. One was a commercially-available, steel-filled, variable mix-ratio, coating resin, sold as Furane Epocast. No. 9 lead shot in CIBA epoxy was also tested. The ability to cast the attenuators in the required shape is very desirable, so only thermosetting plastics were considered for porous compounds. The previously used CIBA epoxy was made porous by the addition of "micro balloons" which are resinous, air-filled bubbles of random sizes up to 0.15 mm in diameter. The Furane Epocast was also made porous in the same manner. A very weak and compressible electrical plotting compound, Biwax No. 637, was also tested, primarily out of curiosity. It does not have enough structural integrity to function as an attenuator but seemed likely to provide significant damping.

A total of eight different samples of these compounds was made by varying hardness and porosity. Sound speed was measured and an indication of acoustic attenuation was obtained for each of these by dropping a steel ball on one end of a cylindrical sample and recording the pulse transmitted through it. Table 1 summarizes the measured properties of these materials. The following general observations were made: (1) sound speed was increased and attenuation slightly reduced by the addition of porosity (in the range of 17 percent to 31 percent porosity) in both CIBA and Furane epoxies; (2) the steel-filled epoxy was not significantly different than the unfilled CIBA; (3) the lead shot resulted in a slight increase in attenuation (25 percent increase in 30 cm of length) in CIBA; and, (4) a large attenuation (90 percent in 30 cm) was obtained from the soft Furane samples. Thus, it appeared that the only mechanism which provided significant attenuation was visco-elastic damping in the soft materials, and that porosity and multi-point scattering were quite ineffective.

Table 1. Physical properties and drop-ball test results of attenuating materials.

	Density	Sound Speed (mm/μs)	Drop-Ball Test Output Pulse Relative Amplitude	Drop-Ball Test Output Pulse Width (μs) (FWHM)
Biwax	1.06	0.26	0.001	200
Soft, Steel-Filled Epoxy[1]	1.77	0.81	0.070	150
Soft, Steel-Filled Epoxy[2] (with 25% Porosity)	1.32	1.03	0.130	75
CIBA Epoxy (with 57% Lead Shot)	6.92	1.25	0.740	20
CIBA Epoxy	1.15	1.71	1.100	20
CIBA Epoxy[2] (with 17% Porosity)	0.95	1.75	1.100	20
Hard, Steel-Filled Epoxy[3]	2.22	1.80	1.200	17
CIBA Epoxy[2] (with 31% Porosity)	0.79	1.80	1.400	18

[1] Furane Epocast. Contains about 9% steel powder. Resin-to-hardener ratio 10:3. Compressive strength 0.3 kbar.

[2] Samples made porous by adding microballoons. Balloon sizes appeared random in the range of 0 to 0.15 mm.

[3] Furane Epocast mixed 10:1. Contains 15% steel powder. Compressive strength 0.6 kbar.

Complete elliptical attenuators were then cast onto three 30-cm tapered bars, two using the soft, steel-filled epoxy, (one dense and another with 25 percent porosity) and one using porous CIBA. The shorter bars were used to reduce the labor of shaping the attenuators. Although the porous CIBA did not attenuate well in the initial tests with cylindrical samples, its impedance was nearly identical to the two Furane samples and it could therefore be cast in the same mold with little additional effort. To make the mold, an aluminum pattern was machined to the appropriate elliptical shape and silicone rubber was ast around it. When the aluminum was removed, the rubber formed a mold suitable for a material having the specific acoustic impedance used to determine the shape of the ellipse. This rather laborious process must be repeated for each material of differing impedance.

These three samples were then built into bar gauges with quartz sensors and 15-cm input bars. Drop-ball tests confirmed the presence of a very large reflection from the end of the CIBA bar but showed no reflection at all from the two Furance samples (see Figure 4). However, drop-bar tests on the two Furance gauges showed a very significant decay in what should be an approximately square-wave pulse. As shown in Figure 5, the signal fell to 60 percent of the peak value before the drop bar rebounded at 1.1 ms. The CIBA gauge did not show this effect but, as expected, its signal lasted for only about 0.5 ms before being cancelled by the reflection.

The fact that the decay in the signal from the Furane gauges begins promptly after the peak is reached implies that it is unrelated to reflections from the end of the gauge. Instead, the decay must be due to environment experienced by the pressure pulse as soon as it enters the tapered region of the steel bar. This could result from an undervaluation of the impedance of the Furane compounds. However, its presence in the Furane bars and absence in the CIBA bar casts suspicion on the most apparent difference in these two materials - CIBA is a very rigid plastic, while Furane is quite flexible. Considerable shearing is to be expected in in such a flexible material when loaded in a non-uniform manner. Reflection of shear waves from the elliptical surface of the attenuator could conceivably generate relief waves of sufficient amplitude to account for the decay in the gauge signal on the drop-bar test.

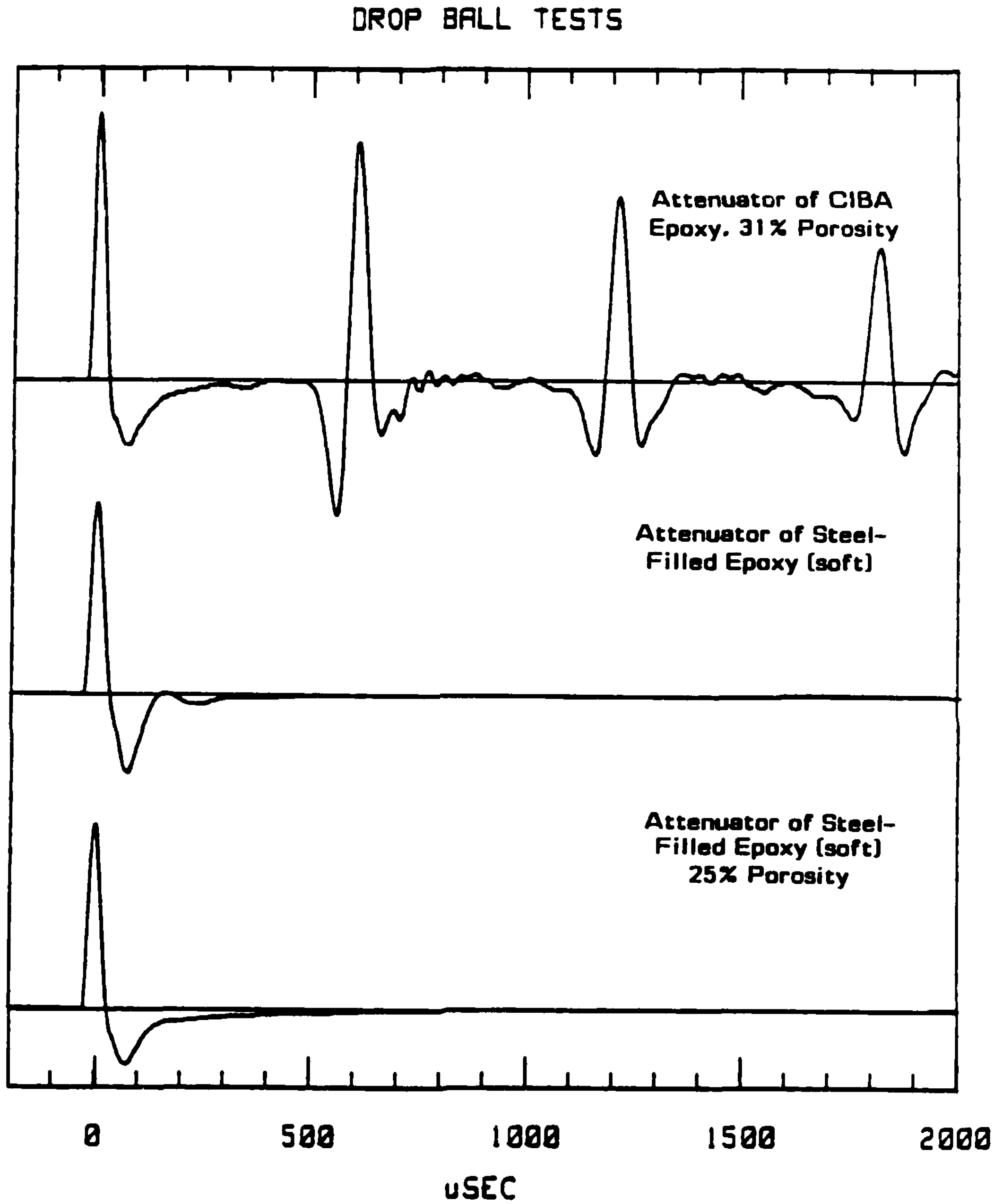


Figure 4. Signals from drop-ball impacts on gauges with three types of attenuators. The multiple pulses in the top trace are caused by reflections from the end of the attenuator. The reflections were completely damped by the steel-filled, soft attenuators.

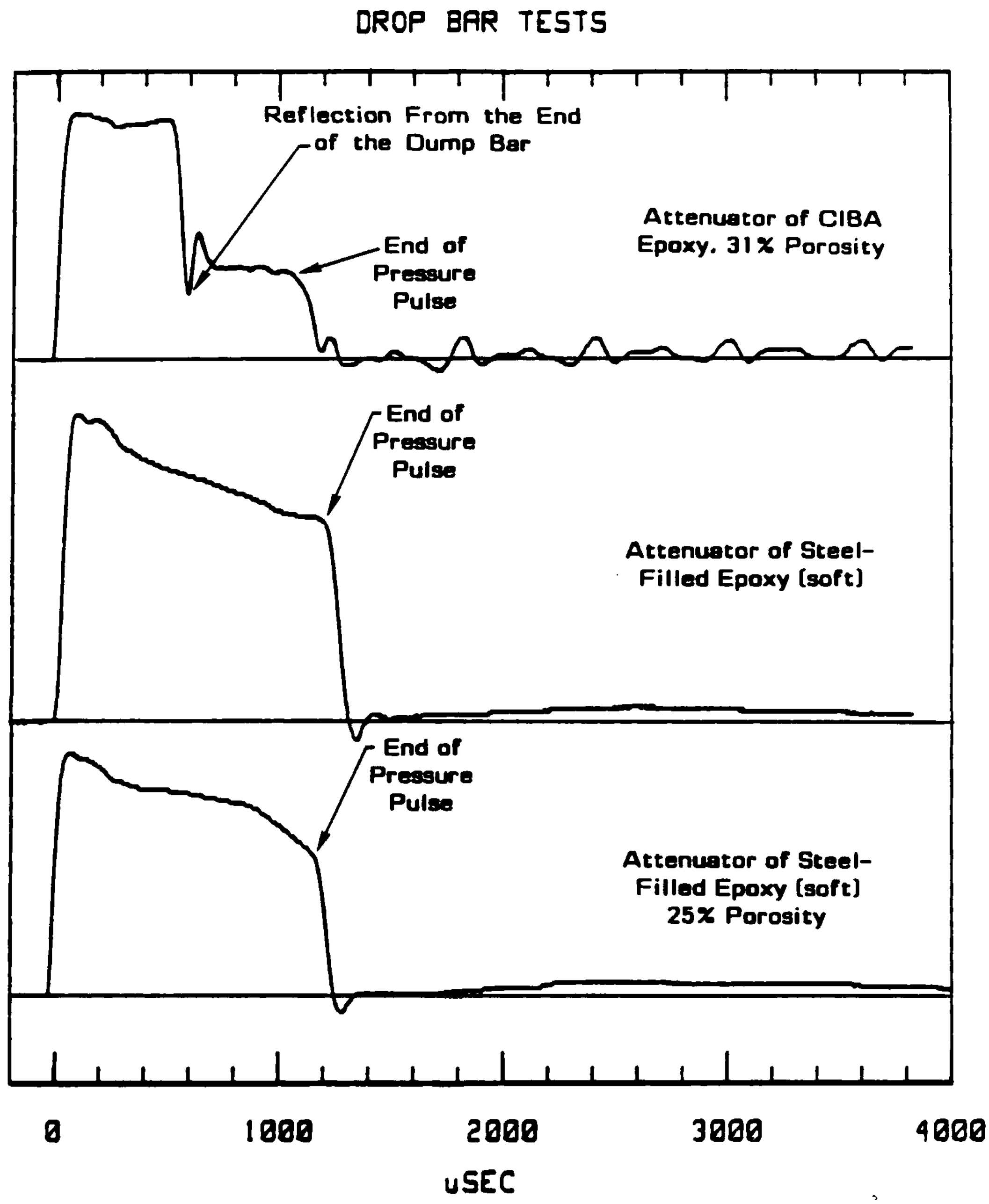


Figure 5. Signals from drop-bar impacts on the same gauges of Figure 4. The lower two traces show the full 1.1 ms width of the input pulse but decay about 40 percent during this time. The upper trace for the gauge with the hard epoxy attenuator shows no decay but is strongly perturbed by the first reflection from the end of the attenuator at 0.6 ms.

A gauge was then built which had a cylindrical Furane attenuator cast on a 30 cm long tapered bar. The purpose of this gauge was to determine if the decay seen previously was due to some intrinsic property of the soft plastic or, perhaps, due to a miscalculation of the shape of the ellipsoid used in the previous gauge. The cylindrical encapsulation should increase the effective impedance of the dump bar and cause a positive reflection of the stress pulse as it reaches the encapsulated region. A similar effect is quite readily observable in conventional bar gauges where a rigid clamp on the bar, or even the soft rubber spacers used to center the bar in its protective tube, can cause a reflection.

Quite surprisingly, this gauge produced a waveform nearly identical to that seen in the previous gauge with the elliptical attenuator. The signal decayed to 53 percent of the peak value in 0.5 ms and, in particular, showed no indication of a reflection from the top of the attenuator. This destroyed the hope of correcting the decay by increasing the diameter of the attenuator and, in fact, implied that the elliptical shape is not essential at all for such materials. Perhaps the softness of the attenuator material prevented the stress wave from interacting fully with the excess Furane outside the elliptical shape. This, in fact, could explain the origin of the decay seen in these signals. If the wave does not interact with the outer region of the Furane, when the net impedance of the attenuator assembly would be continuously reduced as the pulse propagates down the tapering dump bar. This would result in a continuous negative reflection which, when added to the incoming pressure wave, would cause the gauge output signal to decay.

In an attempt to control this problem, a gauge was made for which the tapered bar was dipped into the soft Furane epoxy (which was allowed to cure) and then cast in a rigid, porous, CIBA attenuator. The results from this gauge were essentially the same as those from the single-component, porous CIBA attenuator - a very large reflection was produced from the end of the plastic.

The only remaining variable which might help control the signal decay observed with the soft attenuators was the length of the tapered bar. It seemed reasonable that a more gradual taper to the dump bar, with a correspondingly more gradual build-up of the attenuator material, would help. To test this, a new gauge was built with a Furane attenuator on one of the 91 cm long tapered bars used in the original tests. For comparison, a conventional bar gauge with a 91 cm untapered dump bar was also built. These gauges were tested with a drop bar that produced a pulse with a 470 μs duration, 140 μs longer than the recording time of the standard gauge.

Results of these tests are shown in Figure 6. As expected, the signal from the conventional bar gauge ended abruptly when the reflection from the end of the dump bar returned to the crystal. However, the tapered bar gauge, with a dump bar of the same length, faithfully recorded the entire pressure pulse. The small negative peak at approximately 1.5 ms is believed to be the reflection from the end of the attenuator. It is possible that the attenuator needs to be extended beyond the tip of the tapered bar to provide additional attenuation and completely eliminate this reflected signal.

It can be seen in Figure 6 that the pressure pulse recorded by the damped bar gauge reached a peak at about 200 μs and decayed by about 5 percent before the pulse ended with the rebound of the drop bar. Most of this decay occurs after the signal from the standard bar gauge is terminated by the reflection, so it is not known if the decay is a real characteristic of the pressure pulse or an artifact of the damped bar gauge. It may very well be all that remains of the 40 percent decay observed with the previous 30 cm long tapered bar. Additional testing, with square-wave pulses having a longer duration, would be required to determine this.

The performance of the gauge with the 91 cm long tapered bar was very encouraging. Apparently, the taper on the 30 cm bar was too abrupt to allow the pulse to couple properly into the attenuator. However, it is not clear that the 91 cm bar is sufficiently long, as the signal from this gauge is beginning to decay when the drop bar rebounds. This fall-off is insignificant compared to that of the 30 cm bar, but could become more apparent with a pressure signal having a longer duration.

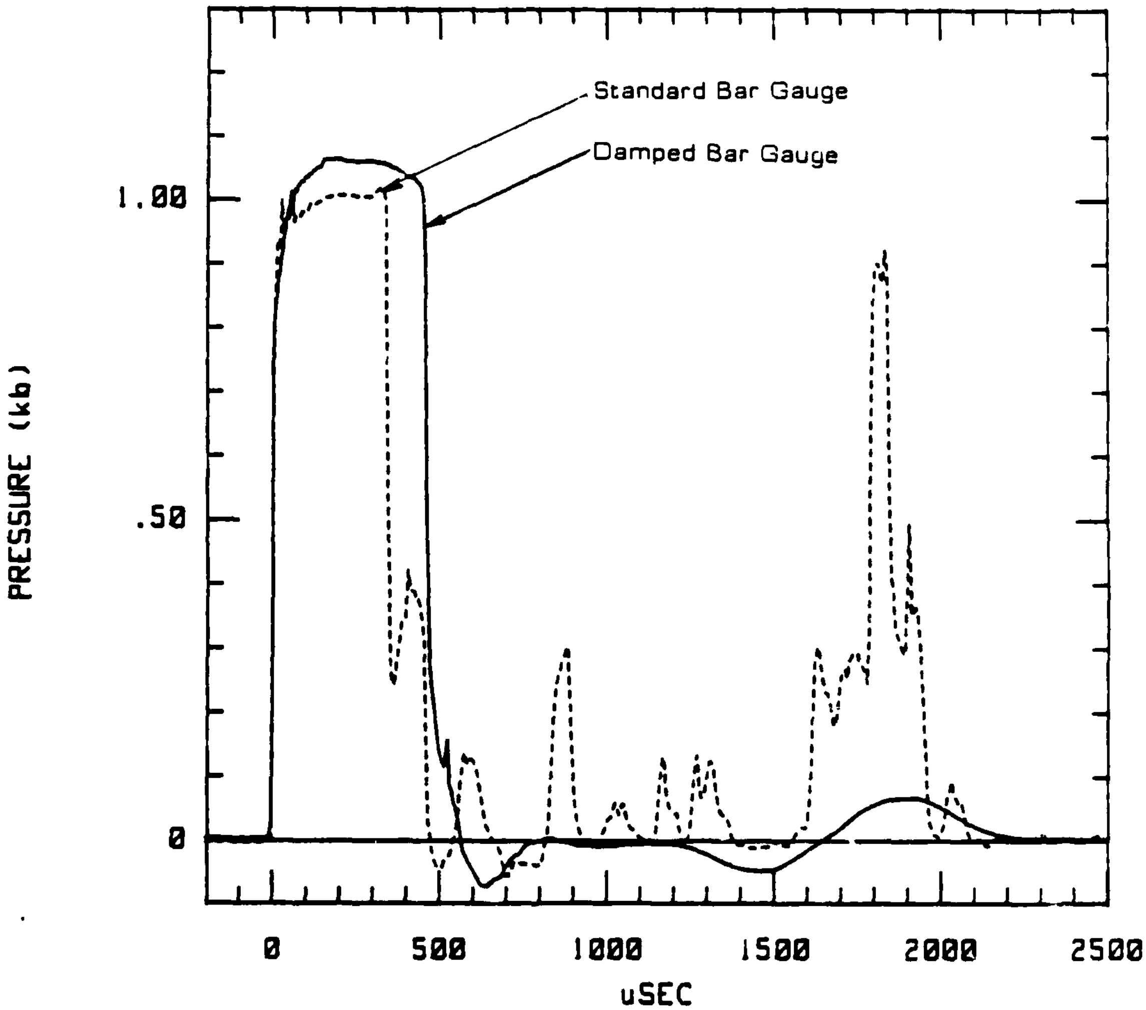


Figure 6. Comparison of a damped bar gauge having a 91 cm long tapered bar with a standard bar gauge of the same length. The longer taper appears to have eliminated the fall-off of the signal observed with the 30-cm-long tapered bars (Figure 5).

SECTION 5
CONCLUSIONS

The extension of Edwards' technique to the pressure range of several kilobars has been demonstrated. Bar gauges have been produced and successfully tested which showed that a relatively high-level stress pulse could be coupled gradually from a high-impedance medium to one of much lower impedance, without generating any discernible reflection.

Developing an attenuator which can absorb the pulse within the dump bar assembly proved to be more difficult. The materials which initially were thought to be most likely to produce an acceptable attenuator (basically porous materials and multi-component materials which would produce multiple-point scattering) proved quite ineffective in the limited number of samples tested. However, the soft, viscoelastic Furane epoxy has proven to be a very good attenuator. Although this epoxy is steel-filled, it appears that the only effective quality is its softness. The unique decay in the pressure signal produced by a gauge having a 30 cm long attenuator of soft Furane is not completely understood, but was found to be essentially non-existent with a 91 cm long attenuator when tested with a 0.5-ms-wide pressure pulse. It could, however, become apparent again with a pressure signal having a longer duration. Apparently, the taper on the 30 cm long bar was too abrupt to allow the pulse to couple properly into the attenuator. If so, this indicates that the simple acoustic principles used to derive the shape of the attenuator are not sufficient to accurately describe the process. The fact that a cylindrical attenuator of soft Furane on a tapered bar performs as well as one having the elliptical shape specified by theory, also indicates a problem with the theory.

Fielding of the damped bar gauge on large-scale HE tests was not conducted on this contract because the gauge was not sufficiently developed to justify the expense. This work is to be continued under another contract and we expect to test (with a longer input pulse) this gauge and similar gauges with longer tapered bars. To simulate the gradual unloading which typically occurs with explosively-driven waves, we also plan to do testing with a specially-shaped drop bar to provide a step unloading instead of an abrupt rebound. The possibility of using a cylindrically-shaped attenuator will be pursued and, if sucessful, would considerably simplify further testing and eventual guage production for fielding.

SECTION 6
LIST OF REFERENCES

1. Ben Veniste, Y., and Abondi, J., J. Sound and Vibration 46, p. 473, (1976).

2. Edwards, D.H., Davies, L., and Lawrence, T.R., J. Sci. Instr. 41, p. 609, (1964).

3. Faustov, Yu. K., and Rakhshtadt, A.G., Nauk. Izv. Ahad., SSSR, Metally, 5, p. 203, (1971).

4. Gurtman, G.A., and Hegemier, G.A., Int. J. Solids Structures, 11, p. 973, (1975).

5. Harpavat, G.L., "Measurement of Carrier Bead Velocity Distribution in Cascade Flow", IEEE Transactions on Industry Relations, Vol. AA-16, No. 4, p. 582, July/August, (1980).

6. Hegemier, G.A., Gurtman, G.A., and Nayfeh, A.H., Int. J. Solids Structures 9, p. 395, (1973).

7. Ivanova, L.A., Kondrat'yeva T.C., and Scherbo, M.N., Phys. Solid Earth 2, p. 81, (1970).

8. McIntosh, M.K., J. Phys. Eng. 4, p. 145, (1971).

9. Metha, C.H., Geophysics 48, p. 1359, (1983).

10. Peck, J.C., "Shock and Mechanical Properties of Solids", Burke, J.J., and Weiss, J., editors, Proceedings of the 17th Sagamore Army Materials Conference, Syracuse Univ. Press, (1971).

11. Peck, J.C., and Gurtman, G.A., J. Appl. Mech. 36, p. 479, (1969)

12. Ragland, K.W., Cullen, R.E., Rev. Sci, Instr. 38, p. 740, (1967).

13. Vintaykin, Ye. Z., Litvin, D.F., and Udovenko, V.A., Phys. Met. Metallog. 37, p. 92, (1964).

14. Whittier, J.S., and Peck, J.C., J. Appl. Mech. 36, p. 485, (1969).

DISTRIBUTION LIST

DEPARTMENT OF DEFENSE

DEFENSE ADV RSCH PROJ AGENCY
ATTN: DIRECTOR

DEFENSE INTELLIGENCE AGENCY
2 CYS ATTN: RTS-2B

DEFENSE NUCLEAR AGENCY
ATTN: DFRA
ATTN: OPNA
ATTN: OPNS
ATTN: RAEV
ATTN: SPSD
ATTN: SPWE
12CYS ATTN: TDTR
4 CYS ATTN: TITL

DEFENSE NUCLEAR AGENCY
ATTN: TDNV

DEFENSE NUCLEAR AGENCY
ATTN: TDTT
ATTN: NMENIN

DEFENSE TECH INFO CENTER
12CYS ATTN: DD

DEPT OF DEF EXPLO SAFETY BOARD
ATTN: CHAIRMAN

LAWRENCE LIVERMORE NATIONAL LAB
ATTN: DNA-LL

NATIONAL SECURITY AGENCY
ATTN: DIRECTOR

DEPARTMENT OF THE ARMY

HARRY DIAMOND LABORATORIES
ATTN: C KENYON
ATTN: J MESZAROS
ATTN: M BUSHELL
ATTN: J BLACKBURN
ATTN: J VANDERWALL
ATTN: G MERKEL
ATTN: R GILBERT

U S ARMY ATMOSPHERIC SCI LAB
ATTN: COMMANDER/DIRECTOR

U S ARMY BALLISTIC RESEARCH LAB
ATTN: P HOWE

U S ARMY COLD REGION RES ENGR LAB
ATTN: TECHNICAL DIRECTOR

U S ARMY COMM R&D COMMAND
ATTN: COMMANDER

U S ARMY ELECTRONICS R & D COMMAND
ATTN: DELET-ER
ATTN: DRSL

U S ARMY ENGINEER DIV HUNTSVILLE
ATTN: COMMANDER

U S ARMY ENGR WATERWAYS EXPER STA
ATTN: J INGRAM
ATTN: R WELCH
ATTN: R WHALIN
ATTN: J K INGRAM

U S ARMY STRATEGIC DEFENSE CMD
ATTN: DASD-PP

U S ARMY STRATEGIC DEFENSE CMD
ATTN: R K DUDNEY

U S ARMY STRATEGIC DEFENSE COMMAND
ATTN: ATC
ATTN: F HOKE

USA ELECT WARFARE/SEC,
SURV & TARGET ACQ CTR
ATTN: S KRONENBERG

DEPARTMENT OF THE NAVY

DAVID TAYLOR NAVAL SHIP R & D CTR
ATTN: CODE 1

NAVAL SURFACE WARFARE CENTER
ATTN: J FORBES
ATTN: R TUSSING

NAVAL WEAPONS CENTER
ATTN: G GREENE

NAVAL WEAPONS EVALUATION FACILITY
ATTN: CLASSIFIED LIBRARY

OFFICE OF NAVAL TECHNOLOGY
ATTN: CODE 217

DEPARTMENT OF THE AIR FORCE

AIR FORCE ARMAMENT LABORATORY
ATTN: M ZIMMER

AIR FORCE OFFICE OF SCI RSCH
ATTN: AFOSR/NA

AIR FORCE WEAPONS LABORATORY
ATTN: C AEBY
ATTN: NTED
ATTN: D COLE
ATTN: J RENICK
ATTN: NTEO

DEPARTMENT OF ENERGY

DEPARTMENT OF ENERGY
ALBUQUERQUE OPERATIONS OFFICE
ATTN: DIRECTOR, OSPA

EG&G ENERGY MEASUREMENTS
ATTN: W R KITCHEN

LAWRENCE LIVERMORE NATIONAL LAB
ATTN: B BOWMAN
ATTN: E LEE
ATTN: G E VOGTLIN

ATTN: W E FARLEY
ATTN: W A BOOKLESS

LOS ALAMOS NATIONAL LABORATORY
ATTN: C S YOUNG
ATTN: D EILERS
ATTN: DIRECTOR
ATTN: G BARRASCH
ATTN: G M SMITH
ATTN: J OGLE
ATTN: M PONGRATZ
ATTN: M WILKE
ATTN: S STONE
ATTN: T MCKOWN

OAK RIDGE NATIONAL LABORATORY
ATTN: D BARTINE
ATTN: DIRECTOR
ATTN: R L ANDERSON

SANDIA NATIONAL LABORATORIES
ATTN: J S PHILLIPS
ATTN: C W COOK
ATTN: S R DOLCE
ATTN: C W SMITH

OTHER GOVERNMENT

DEPARTMENT OF COMMERCE
ATTN: SEC OFC FOR INSTR DIV
ATTN: O PETERSONS
ATTN: SEC OFC FOR OFFICE OF DIR
ATTN: R H MCKNIGHT

DEPARTMENT OF COMMERCE
ATTN: G REEVE

FEDERAL EMERGENCY MGT AGENCY
ATTN: J F JACOBS

DEPARTMENT OF DEFENSE CONTRACTORS

ACUREX CORP
ATTN: W DEAN

ADVANCED RESEARCH & APPLICATIONS CORP
ATTN: J STANLEY
ATTN: M BOYLE
ATTN: R ARMISTEAD

APPLIED RESEARCH ASSOCIATES, INC
ATTN: N HIGGINS

APTEK, INC
ATTN: T MEAGHER

ASTRON RESEARCH & ENGINEERING
ATTN: J HUNTINGTON

CALIF RESEARCH & TECHNOLOGY, INC
ATTN: K KREYENHAGEN
ATTN: M ROSENBLATT
ATTN: S SCHUSTER

CALIF RESEARCH & TECHNOLOGY, INC
ATTN: J THOMPSON

CALSPAN CORP
ATTN: PRESIDENT

CARPENTER RESEARCH CORP
ATTN: H J CARPENTER

CHARLES STARK DRAPER LAB, INC
ATTN: P KELLY

CUSHING ASSOCIATES, INC
ATTN: V CUSHING

ECTRON CORP
ATTN: E CUNNINGHAM

EG&G WASH ANALYTICAL SVCS CTR, INC
ATTN: A BONHAM
ATTN: G SOWER
ATTN: M GRUCHALLA

EG&G/KIRTLAND
ATTN: S ORRELL

EG&G, INC
ATTN: E C SHIVERS
ATTN: L F SANDOVAL
ATTN: N F COCHRANE
ATTN: P A ZAGARINO
ATTN: R D SENO

FORD AEROSPACE CORPORATION
ATTN: TECH INFO SVCS

G B LABORATORY, INC
ATTN: G BURGHART

GENERAL RESEARCH CORP
ATTN: E STEELE
ATTN: R GLOBUS

GEO CENTERS, INC
ATTN: E MARRAM
ATTN: H LINNERUD

GEOSCIENCE LTD
ATTN: DR H POPPENDIEK

H-TECH LABS, INC
ATTN: B HARTENBAUM

HTL K WEST
ATTN: A D GOEDEKE

IIT RESEARCH INSTITUTE
ATTN: DIRECTOR

JAYCOR
ATTN: R BONN

JAYCOR
ATTN: PRESIDENT

KAMAN SCIENCES CORP
ATTN: B TAYLOR
ATTN: C HUDSON
ATTN: D ELDER
ATTN: D OSBORN

ATTN: E COLE
ATTN: F RICH
ATTN: G ROARK
ATTN: N KOOZER

KAMAN SCIENCES CORP
ATTN: E CONRAD

LOS ALAMOS TECHNICAL ASSOCIATES, INC
ATTN: PRESIDENT

MITRE CORPORATION
ATTN: J E DRIVER

NEW MEXICO ENGINEERING RSCH INSTITUTE
ATTN: DIRECTOR

PACIFIC-SIERRA RESEARCH CORP
ATTN: H BRODE
ATTN: R SMALL

PACIFIC-SIERRA RESEARCH CORP
ATTN: G MCCLELLAN

PACIFICA TECHNOLOGY
ATTN: R ALLEN

PHYSICAL DYNAMICS, INC
ATTN: B KREISS

PHYSICS APPLICATIONS, INC
ATTN: DOCUMENT CONTROL

PHYSICS INTERNATIONAL CO
ATTN: G MANKINEN
ATTN: P CAYERE
ATTN: R Z CONROW

R & D ASSOCIATES
ATTN: C K B LEE
ATTN: D HOLLIDAY
ATTN: D SIMONS
ATTN: J LEWIS

RAND CORP
ATTN: P DAVIS

RAND CORP
ATTN: B BENNETT

RAYTHEON CO
ATTN: J WECKBACK

RIVERSIDE RESEARCH INSTITUTE
ATTN: PRESIDENT

S-CUBED
ATTN: C PETERSEN
ATTN: D GRINE
ATTN: P COLEMAN
2 CYS ATTN: R WILSON

SCIENCE & ENGRG ASSOCIATES, INC
ATTN: J CRAMER

SCIENCE & ENGRG ASSOCIATES, INC
ATTN: R BEATY

SCIENCE APPLICATIONS INTL CORP
ATTN: K SITES
ATTN: L A MILLONZI

SCIENCE APPLICATIONS INTL CORP
ATTN: R SCHLAUG

SCIENCE APPLICATIONS INTL CORP
ATTN: B GORDON
ATTN: E TOTON
ATTN: S METH

SRI INTERNATIONAL
ATTN: D KEOUGH
ATTN: E VANCE
ATTN: P DE CARLI

TELEDYNE BROWN ENGINEERING
ATTN: PRESIDENT

WASHINGTON STATE UNIVERSITY
ATTN: PROF G DUVALL
ATTN: PROF. Y GUPTA